

CP Violation in $B_s^0 \rightarrow J/\psi\phi$

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Study of CP violation in the decay channel $B_s^0 \rightarrow J/\psi\phi$ is essential to exploring and constraining physics beyond the Standard Model in the quark flavour sector. The experimental progress in this area of activity at the LHC and Tevatron is discussed.

I. PROBING NEW PHYSICS IN $B_s^0-\bar{B}_s^0$ MIXING WITH $B_s^0 \rightarrow J/\psi\phi$

The origins of CP violation in fundamental physics theory remain a mystery. The B_s^0 system provides excellent laboratories to probe CP violating new physics, since new particles beyond the Standard Model (SM) may enter the loop-mediated B_s^0 meson mixing process, leading to discrepancies of CP asymmetries with their SM expectations.

The effective Hamiltonian of the $B_s^0-\bar{B}_s^0$ system can be written as

$$\mathbf{H}_s = \begin{pmatrix} M_{11}^s & M_{12}^s \\ M_{12}^{s*} & M_{22}^s \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11}^s & \Gamma_{12}^s \\ \Gamma_{12}^{s*} & \Gamma_{22}^s \end{pmatrix}, \quad (1)$$

where $M_{11}^s = M_{22}^s$ and $\Gamma_{11}^s = \Gamma_{22}^s$ hold under the assumption of CPT invariance. The off-diagonal elements M_{12}^s and Γ_{12}^s are responsible for $B_s^0-\bar{B}_s^0$ mixing. Diagonalizing the Hamiltonian matrix leads to the two mass eigenstates $B_{H,L}^s$ (H and L denote heavy and light, respectively), with mass $M_{H,L}^s$ and decay width $\Gamma_{H,L}^s$. $B_{H,L}^s$ are linear combinations of flavour eigenstates with complex coefficients p and q that satisfy $|p|^2 + |q|^2 = 1$: $|B_{L,H}^s\rangle = p|B_s^0\rangle \pm q|\bar{B}_s^0\rangle$. New physics contribution in the mixing process could affect the mass difference between the heavy and light mass eigenstates, $\Delta m_s \equiv M_H^s - M_L^s$, the decay width difference between the light and heavy mass eigenstates, $\Delta\Gamma_s \equiv \Gamma_L^s - \Gamma_H^s$, and the semileptonic asymmetry $a_{SL}^s \approx \frac{|\Gamma_{12}^s|}{|M_{12}^s|} \sin\phi_{12}^s$, where $\phi_{12}^s \equiv \arg(-M_{12}^s/\Gamma_{12}^s)$ is a convention-independent phase difference.

The decay $B_s^0 \rightarrow J/\psi\phi$ (charge conjugate is implied in this paper) proceeds dominantly via a tree level $b \rightarrow c\bar{c}s$ diagram that is well understood in the SM. This makes it an ideal place to search for demonstration of new physics with only limited hadronic uncertainties. Ignoring the doubly Cabibbo-suppressed penguin contributions in the $b \rightarrow c\bar{c}s$ decay process, we denote the phase difference between the amplitude for a direct decay of B_s^0 to a CP eigenstate f with eigenvalue η_f and the amplitude for decay after oscillation as

$$\phi_s \equiv -\arg\left(\eta_f \frac{q}{p} \frac{\bar{A}_f}{A_f}\right) \approx \arg(-M_{12}^s) - 2\arg(V_{cb}V_{cs}^*), \quad (2)$$

where A_f and \bar{A}_f are the decay amplitudes of $B_s^0 \rightarrow f$ and $\bar{B}_s^0 \rightarrow f$, respectively. (Discussions about controlling the effect of the penguin diagrams in the $b \rightarrow c\bar{c}s$ decay process can be found in Section 3.2. of Ref. [1] and references therein.) ϕ_s is very precisely predicted within the SM, $\phi_s^{\text{SM}} = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.036 \pm 0.002$ rad [2, 3], however, it could be altered by new physics contribution in B_s^0 mixing. Note $\phi_s \approx \phi_{12}^s$ is a good approximation unless either the $b \rightarrow c\bar{c}s$ decay process or Γ_{12}^s is affected by physics beyond the SM.

Neglecting the small CP violation in B_s^0 mixing, *i.e.* assuming $|q/p| = 1$, we can write the mixing-induced CP asymmetry as $S_f = -\sin\phi_s$. Thus ϕ_s can be extracted from the time-dependent CP asymmetry in the decay $B_s^0 \rightarrow J/\psi\phi$, measurement of which requires to identify the flavour of the initial B_s^0 or \bar{B}_s^0 mesons. The final state of the decay $B_s^0 \rightarrow J/\psi\phi$ is an admixture of two CP -even and one CP -odd eigenstates. There is also a CP -odd final state due to S-wave K^+K^- contribution (specified using the subscript “S”) under the ϕ peak. An angular analysis is needed to statistically disentangle the four CP eigenstates [4, 5]. The differential rates in decay time and angular variables for the decay $B_s^0 \rightarrow J/\psi\phi$ are given in the references [4–6]. The time-dependent angular analysis of flavour tagged $B_s^0 \rightarrow J/\psi\phi$ decays also needs to take into account the experimental effects such as background contamination, detector resolution and reconstruction efficiency.

II. HISTORICAL REVIEW OF THE EXPERIMENTAL STUDY

The decay $B_s^0 \rightarrow J/\psi\phi$ has been extensively studied at the Tevatron and LHC experiments [7–10]. Early study at CDF and D0 experiments each using an integrated luminosity of 2.8 fb^{-1} showed a 2.1σ deviation from their SM expectations (Fig. 1) [7]. However, this was not confirmed by the CDF updated result using 5.2 fb^{-1} of data [8] and the D0 updated result using 8.0 fb^{-1} of data [9], nor by the much more precise LHCb result based on 0.37 fb^{-1} of pp collision data (Fig. 2 (left)) [10]. Furthermore, following the method described in Ref. [6], LHCb used the 0.37 fb^{-1} sample to measure the phase difference between the S-wave and P-wave amplitudes as a function of the K^+K^- invariant mass for each of the two ambiguous solutions (see Fig. 2 (left)) and identified the solution with a decreasing trend as the physical solution (solution I in Fig. 2 (right)). This determined the sign of $\Delta\Gamma_s$ to be positive with a 4.7σ significance [11], and resolved the two-fold ambiguity of ϕ_s for the first time. The remaining solution of ϕ_s and $\Delta\Gamma_s$ in the LHCb analysis of $B_s^0 \rightarrow J/\psi\phi$ decays was consistent with the SM expectations. The most up-to-date results from the LHCb and CDF experiments will be discussed in details in Section III.

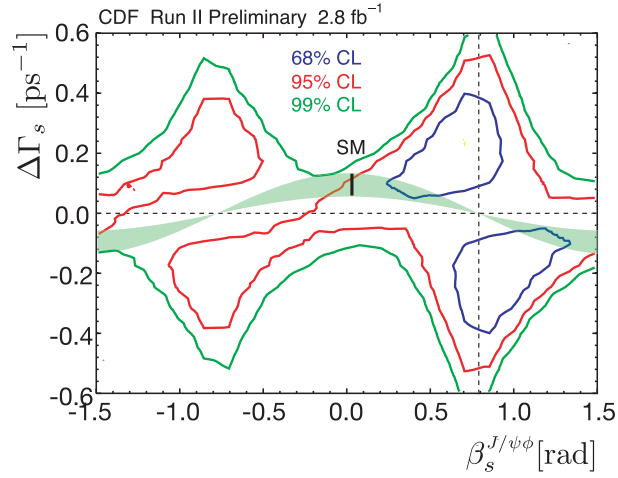


FIG. 1: The confidence regions in the $\beta_s^{J/\psi\phi}$ - $\Delta\Gamma_s$ plane in Ref. [7] from the combination of early D0 and CDF results each based on 2.8 fb^{-1} , where $\beta_s^{J/\psi\phi} = -\phi_s/2$.

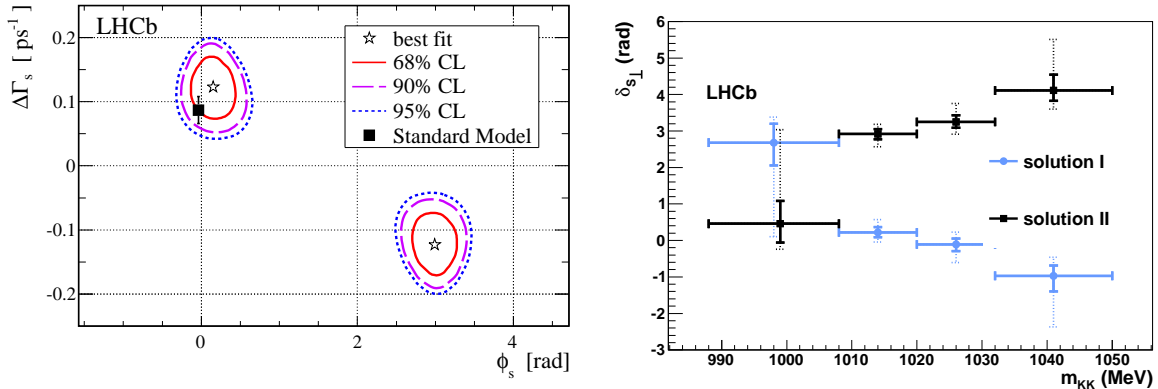


FIG. 2: (Left) The confidence regions in the ϕ_s - $\Delta\Gamma_s$ plane from the LHCb analysis of 0.37 fb^{-1} [10]. (Right) The phase difference between the S-wave and P-wave amplitudes as a function of the K^+K^- invariant mass for each of the two solutions in the $B_s^0 \rightarrow J/\psi\phi$ analysis [11].

III. RECENT EXPERIMENTAL PROGRESSES AND IMPLICATIONS

Recently, LHCb updated its $B_s^0 \rightarrow J/\psi\phi$ analysis result using 1 fb^{-1} of pp collision data collected during the 2011 LHC run at a center of mass energy of $\sqrt{s} = 7 \text{ TeV}$ [12]. A clean sample containing about 21,200 $B_s^0 \rightarrow J/\psi\phi$ signal events in a K^+K^- mass window of 12 MeV around the ϕ mass peak is selected using the particle identification and kinematic information. The reconstructed invariant mass distribution of the selected $B_s^0 \rightarrow J/\psi\phi$ candidates with decay time t above 0.3 ps is shown in Fig. 3 (left), where a J/ψ mass constraint is applied in the vertex fit. These events were triggered by requiring a relatively high transverse momentum muon track from the J/ψ decay to be displaced from the pp interaction point. The trigger efficiency depends on the decay time of the B_s^0 mesons. The geometrical acceptance of the detector and the kinematic requirements on the final state particles also induce a dependence of the reconstruction efficiency as a function of the angular variables. Both efficiency effects are corrected for in the analysis. The background is dominated by combinatorial events and its decay time and angular model is constructed using B_s^0 mass sidebands.

The decay time resolution effect is modelled using a Gaussian model, which has a width $S_{\sigma_t} \cdot \sigma_t$. Here σ_t is the event-by-event decay time resolution. The scale factor S_{σ_t} is estimated to be 1.45 ± 0.06 from a fit to the $t \sim 0$ region (Fig. 3 (right)) and allowed to vary within this uncertainty in the fit for extraction of ϕ_s . This event-by-event resolution model has a statistical power for measurement of mixing-induced CP asymmetries in B_s^0 decays equivalent to that of a single Gaussian model with a constant width of 45 fs.

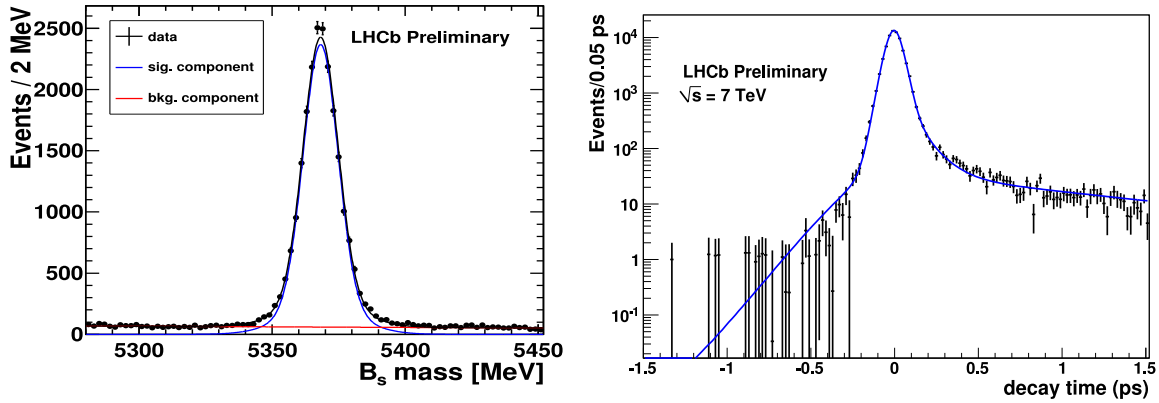


FIG. 3: (Left) Reconstructed invariant mass distribution of the selected $B_s^0 \rightarrow J/\psi\phi$ candidates. (Right) decay time distribution of $B_s^0 \rightarrow J/\psi\phi$ candidates with a true J/ψ including the $t \sim 0$ region and superimposed fit result. Both are from Ref. [12].

In this analysis, the flavour of the B (or \bar{B}) meson at production ($t = 0$) is identified using the opposite side (OS) tagging method, which exploits information about the other b -hadron from pair production of $b\bar{b}$ quarks, including charges of the decay products of the other b -hadron. A wrong tag probability of the OS tagging decision is estimated for each B candidate, and this estimated probability is calibrated in the control channel $B^+ \rightarrow J/\psi K^+$, as shown in Fig. 4 (left). The distribution of calibrated OS wrong tag probability of the tagged $B_s^0 \rightarrow J/\psi\phi$ signal candidates is shown in Fig. 4 (right), from which an average wrong tag probability of $\bar{\omega} = (36.81 \pm 0.18(\text{stat}) \pm 0.74(\text{syst}))\%$ is obtained. The tagging efficiency is $\epsilon_{\text{tag}} = (32.99 \pm 0.33)\%$. The effective tagging efficiency for the $B_s^0 \rightarrow J/\psi\phi$ sample is estimated to be $\epsilon_{\text{tag}}(1 - 2\bar{\omega})^2 = (2.29 \pm 0.07(\text{stat}) \pm 0.26(\text{syst}))\%$.

The analysis uses the B_s^0 oscillation frequency $\Delta m_s = 17.63 \pm 0.11 \text{ ps}^{-1}$ [13] and allows it to float within its uncertainty. The fit projections on the decay time t and the three angular variables are shown in Fig. 5. The

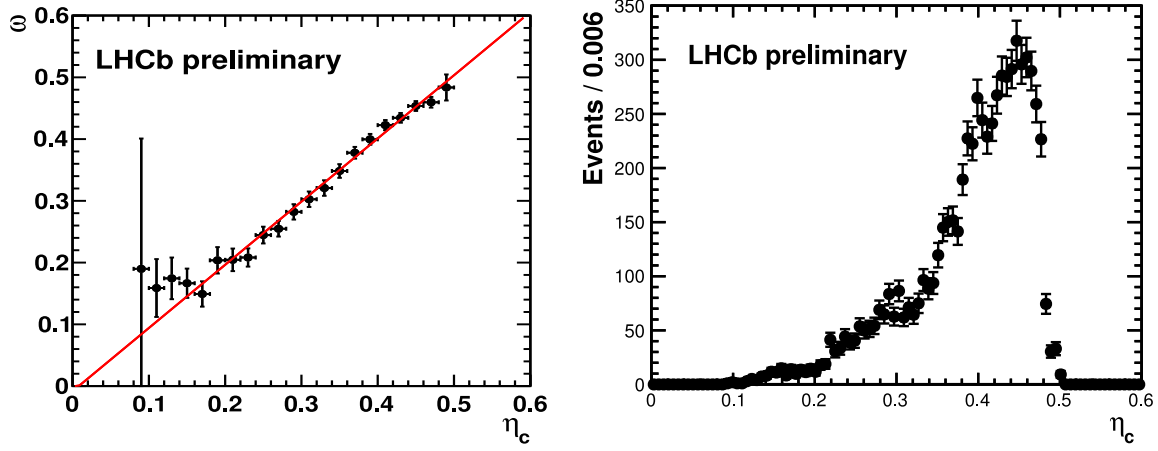


FIG. 4: (Left) Measured OS wrong tag probability (ω) as a function of the estimated OS wrong tag probability (η_c) for background subtracted $B^+ \rightarrow J/\psi K^+$ decays. (Right) Distribution of calibrated OS wrong tag probability of tagged $B_s^0 \rightarrow J/\psi \phi$ signal candidates. Both are from Ref. [12].

numerical results of the major physics parameters are

$$\begin{aligned}
 \phi_s &= -0.001 \pm 0.101 \text{ (stat)} \pm 0.027 \text{ (syst) rad,} \\
 \Gamma_s &= 0.6580 \pm 0.0054 \text{ (stat)} \pm 0.0066 \text{ (syst) ps}^{-1}, \\
 \Delta\Gamma_s &= 0.116 \pm 0.018 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}, \\
 F_S &= 0.022 \pm 0.012 \text{ (stat)} \pm 0.007 \text{ (syst) ,}
 \end{aligned} \tag{3}$$

where F_S is the fraction of S wave contribution in a window of 12 MeV around the ϕ mass. As can be seen in Fig. 6 (left), the measurement of ϕ_s and $\Delta\Gamma_s$ is in good agreement with the SM predictions. These results are still dominated by statistical uncertainties. The important sources of systematic uncertainties include the neglected direct CP violation, insufficient modelling of angular acceptance and background effects. A refined LHCb analysis using the same data sample is in progress. This will include the same side kaon tagging information to increase effective tagging efficiency and also benefit from the improved understanding of the systematic uncertainties.

CDF updated its $B_s^0 \rightarrow J/\psi \phi$ analysis using 9.6 fb^{-1} of $p\bar{p}$ collision data collected at a center of mass energy of $\sqrt{s} = 1.96 \text{ TeV}$ at the Tevatron [14]. Approximately 11,000 signal decays are selected and analyzed. Due to the low decay time resolution, the CDF analysis has limited sensitivity to ϕ_s . The CDF $\Delta\Gamma_s$ result has a precision comparable to that of the LHCb result:

$$\Delta\Gamma_s = 0.068 \pm 0.026 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}. \tag{4}$$

The latest HFAG [15] average of the results from the LHCb [12], CDF [14] and D0 [9] analyses is shown in Fig. 6 (right). The LHCb result dominates the combination, which is in good agreement with the SM predictions. (At the time of writing this article, the ATLAS experiment has also reported the result of a time-dependent angular analysis of $B_s^0 \rightarrow J/\psi \phi$ decays without flavour tagging [16]. We do not discuss this result here.)

In the context of model-independent analysis, the new physics contribution to M_{12}^s can be parameterized using the complex number Δ_s ,

$$M_{12}^s = M_{12}^{s,\text{SM}} \Delta_s. \tag{5}$$

The constraints on Δ_s provided by the current measurements of ϕ_s , Δm_s , Δm_d , $\Delta\Gamma_s$ and semileptonic asymmetries, are shown in Fig. 7 [17]. As can be seen, the major constraints on new physics in M_{12}^s come from the measurements

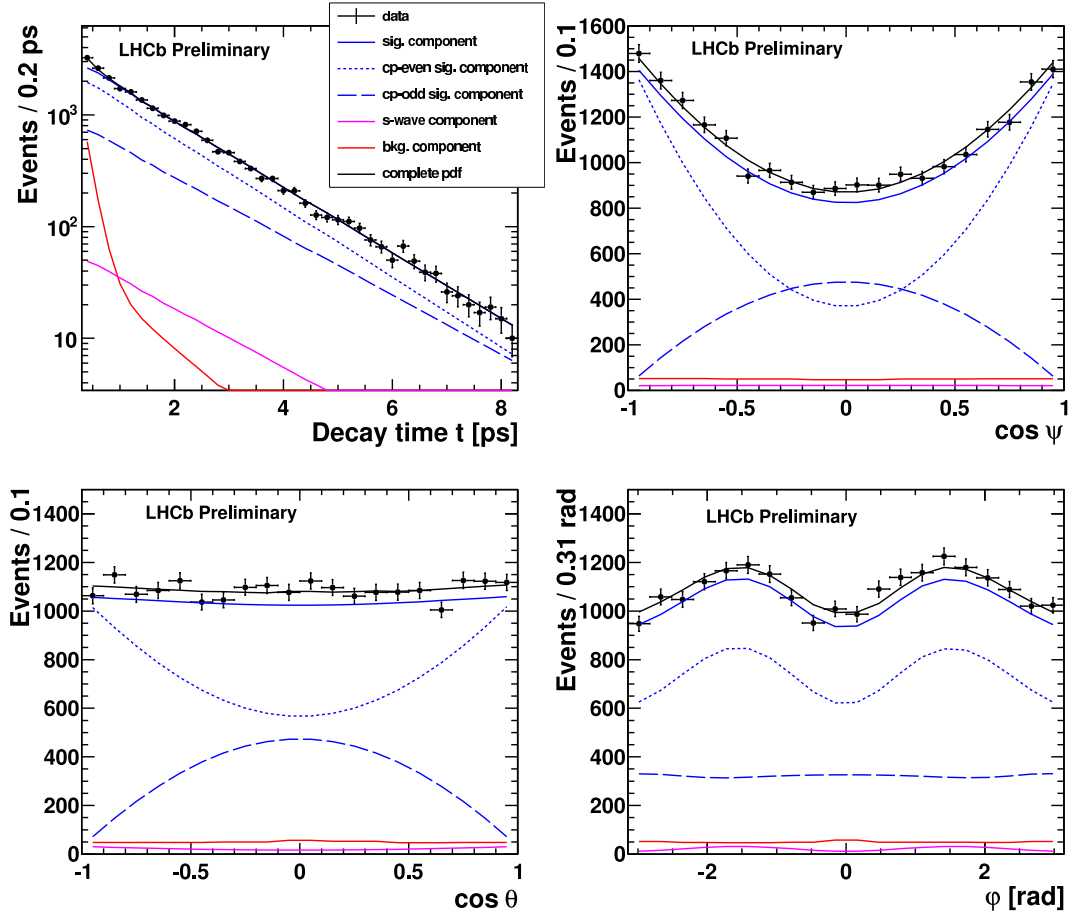


FIG. 5: Data points and fit projections for the decay time and three angular variables for candidates in a ± 20 MeV window around the B_s^0 mass peak [12].

of ϕ_s and $\Delta m_{s/d}$. No significant new physics contribution is identified and the picture of B_s^0 mixing is SM-like. However, up to about 30% new physics contribution in M_{12}^s is still allowed at 3σ confidence level, and probing new physics in B_s^0 mixing at this level requires to improve substantially the measurement precision of ϕ_s . The LHCb experiment is expected to collect 5 fb^{-1} of data before 2018 and 50 fb^{-1} after its upgrade. This will enable LHCb to push down the uncertainty of ϕ_s to ~ 0.025 rad around 2018, and eventually achieve a precision of ~ 0.008 rad after the upgrade [18, 19].

IV. CONCLUSIONS

In summary, the study of CP violation in $B_s^0 \rightarrow J/\psi\phi$ offers a great opportunity to search for physics beyond the SM that enters the B_s^0 mixing process. Significant progress has been made in the measurement of ϕ_s in $B_s^0 \rightarrow J/\psi\phi$, particularly by the LHCb experiment, that allows to put stringent constraints on new physics contribution in B_s^0 mixing. The LHCb experiment aims to greatly improve the ϕ_s measurement precision for probing sub-leading level new physics contribution in B_s^0 mixing.

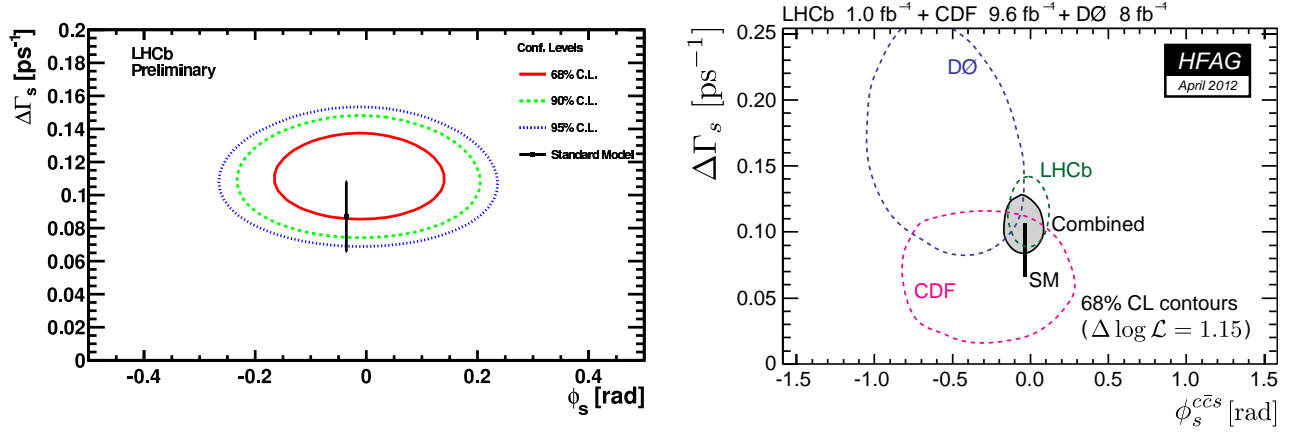


FIG. 6: (Left) LHCb measurement of ϕ_s and $\Delta\Gamma_s$ from $B_s^0 \rightarrow J/\psi \phi$ decays using 1.0 fb⁻¹ [12]. (Right) HFAG 2012 combination of ϕ_s and $\Delta\Gamma_s$ results, where the 1 σ confidence region is shown for each experiment and the combined result [15].

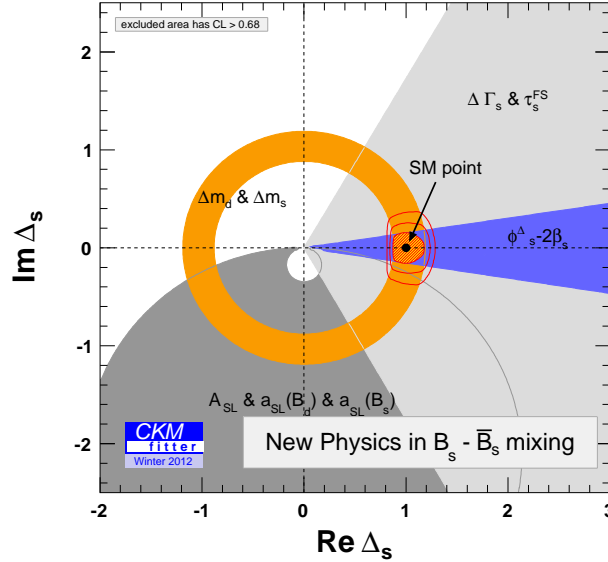


FIG. 7: Model-independent fit [17] in the scenario that new physics affects M_{12}^s . The coloured areas represent regions with CL < 68.3 % for the individual constraints. The red area shows the region with CL < 68.3 % for the combined fit, with the two additional contours delimiting the regions with CL < 95.45 % and CL < 99.73 %.

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